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Engineering property and structural design relationships for new and developing concretes

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ABSTRACT

The paper reports the findings of a study carried out to investigate the effect of new and developing concrete technology solutions, e.g. (i) use of particle packing techniques and fillers to minimise voids, (ii) use of cement additions attained from industrial by-products and (iii) use of high range water-reducing admixtures which enable lower cement contents, on the engineering and structural performance of concrete and implications for structural design. The test programme considered 54 concrete mixes in three series to assess the impact of these on the tensile strength, flexural strength and modulus of elasticity of concrete, and in parallel, 37 mixes to measure these effects on the shear resistance of reinforced concrete beams. The results indicate that the influence of the concretes on compressive strength were generally in proportion to the effects on other engineering properties and were in line with current design assumptions on the behaviour of concrete. Furthermore, EC2 equations for predicting the shear strength of reinforced concrete beams, based on compressive strength, were also found to be appropriate for the range of concrete mixes considered. Overall, the work has demonstrated that new and developing concrete technology solutions can be utilised effectively within the framework of present design procedures and compressive strength is an appropriate parameter for assessing the structural performance of these concretes.

RÉSUMÉ

Le papier rapporte les résultats d'une étude effectuée pour étudier l'effet de nouvelles et se développantes solutions concrètes de technologie, par exemple (i) utilisation des techniques et des remplisseurs d'emballage de particules de réduire au minimum des vides, (ii) utilisation des additions de ciment atteintes des sous-produits industriels et (iii) utilisation des mélanges de réduction de gamme élevée qui permettent le contenu inférieur de ciment, sur la technologie et l'exécution structurale du béton et les implications pour la conception structurale. Le programme d'essai a considéré 54 mélanges de béton dans trois séries évaluer l'impact de ces derniers sur la résistance à la traction, la force flexural et le module d'élasticité de béton, et en parallèle, 37 mélanges pour mesurer ces effets sur la résistance au cisaillement des faisceaux concrets renforcés. Les résultats indiquent que l'influence des bétons sur la résistance à la pression étaient généralement proportionnellement aux effets sur d'autres propriétés de technologie et étaient en conformité avec des prétentions courantes de conception sur le comportement du béton. En outre, les équations EC2 pour prévoir la résistance au cisaillement des faisceaux concrets renforcés, basée sur la résistance à la pression, sont également avérées appropriées pour la gamme des mélanges de béton considérés. De façon générale, le travail a démontré que de nouvelles et se développantes solutions concrètes de technologie peuvent être utilisées efficacement dans le cadre des procédures actuelles de conception et la résistance à la pression est un paramètre approprié pour évaluer l'exécution structurale de ces bétons.

1. INTRODUCTION

In recent years, developments in concrete technology have led to the use of a variety of solutions to improve concrete durability and achieve sustainable concrete

construction. These have included: (i) use of particle packing techniques and fillers to minimise voids [1-3], (ii) use of cement additions attained from industrial by-products [4, 5] and (iii) use of high range water-reducing admixtures which enable lower cement contents [6, 7].

Despite these various developments, which can benefit concrete practice significantly, little attention has been given to the possibility that they may change the engineering performance and that current structural design procedures may not apply.

Furthermore, at present, many standards, for example EC2 [8], assume that the engineering properties of concrete can be approximated from the compressive strength by means of simple relationships (Table 1), independently of the mix constituents. However, it is unclear whether these relationships, formulated primarily from tests on traditional Portland cement concrete, are applicable to concrete mixes that are proportioned using the solutions outlined above. Many structural design equations and rules also incorporate compressive strength, either cylinder strength (f_c) or cube strength (f_{cc}), as a parameter for dealing with many more complex mechanical actions. For example, the EC2 [8] rule for design shear strength of members without shear reinforcement ($v_{Rd,ct}$) is given as,

$$v_{Rd,ct} = V_{Rd,ct}/b_w d$$

$$= [0.11 (1+(200/d)^{1/2}) (100 \rho f_{cc})^{1/3}] \quad (1)$$

where, tension steel ratio $\rho = A_s/b_w d$ and f_{cc} is taken as $1.25 f_c$ (Table 1).

In this rule, the only concrete material parameter is compressive strength, despite the fact that shear forces in a beam without shear reinforcement are resisted by three distinct actions, viz. the combined action of (i) aggregate interlock, (ii) compression zone shear and (iii) the dowel action based on concrete/steel interfacial properties. Again it is unclear whether the assumptions that compressive strength is proportional to increases in aggregate-interlock, compression-zone capacity and dowel-action capacity are applicable to the new types of concrete.

This study was carried out to investigate the effect of these concrete solutions on the engineering properties of concrete, with the main objective of identifying if approaches to mix proportioning or concrete composition influence the applicability of engineering property relationships based on compressive strength given in the

EC2 structural design code. In addition, the study investigated structural performance, to determine if ultimate strength for all concretes can be predicted through compressive strength, as assumed in EC2.

2. PROGRAMME OF WORK

In order to assess the impact of the various concretes on the engineering properties, three series of concretes (Series A, B and C) as listed in Table 2, and covering 54 mixes, were tested. The general approach to proportioning and composition of these was as follows:

- (i) Physical packing techniques including limestone filler, for voids minimisation (Series A).
- (ii) Range of cement combinations (Series B).
- (iii) Variable cement contents, at a fixed w/c ratio, with superplasticizing admixtures (Series C).

In addition, 37 of these mixes (from the three series) were used in a parallel set of tests to assess the effect of mix proportioning on the performance of reinforced concrete beams, with respect to (i) shear resistance, (ii) deformation characteristics and (iii) stress-strain behaviour.

3. MATERIALS

The three common cement types, conforming to BS EN 197-1 [9] used in Series A of the test programme were:

- (i) Portland cement (PC) of strength class 42.5N.
- (ii) Portland-fly ash cement (PC/PFA) comprising PC and 30% pulverized-fuel ash (PFA) conforming to BS 3892: Part 1 [10].
- (iii) Portland blastfurnace cement (PC/GGBS) comprising PC and 40% ground granulated blastfurnace slag (GGBS) conforming to BS 6699 [11].

Table 1 - Stress and deformation characteristics for normal concrete, based on EC2 [8]

MATERIAL PROPERTY	STRENGTH (N/mm ²)/ MODULUS (kN/mm ²)							ANALYTICAL RELATIONSHIP
Characteristic Cylinder Strength, f_c	20	25	30	35	40	45	50	
Characteristic Cube Strength, f_{cc}	25	30	37	45	50	55	60	$f_{cc} \approx 1.25 f_c$
Mean Compressive Strength, f_{cm}	28	33	38	43	48	53	58	$f_{cm} = 0.8 f_{cc} + 8$
Mean Tensile Strength, f_{ctm}	2.2	2.6	2.9	3.2	3.5	3.8	4.1	$f_{ctm} = 0.26 f_{cc}^{(2/3)}$
Characteristic Flexural Strength*, $f_{ct,fl}$	2.9	3.4	3.9	4.3	4.7	5.1	5.5	$f_{ct,fl} = 0.35 f_{cc}^{(2/3)}$
Characteristic Tensile Splitting strength [§] , $f_{ct,sp}$	1.7	2.0	2.3	2.6	2.8	3.1	3.3	$f_{ct,sp} = 0.6 f_{ct,fl}$
Mean Elastic Modulus, E_{cm}	30	31.5	33	34	35	36	37	$E_{cm} = 9.5 (0.8 f_{cc} + 8)^{1/3}$

* and [§] based on references [25] and [26], respectively.

Table 2 - Main parameters investigated in the 3 Series tested

SERIES	NO.OF MIXES	COMMENTS
A	33	3 Cements – PC (CEM I), PC/PFA (CEM II/B-V), PC/GGBS (CEM III-A) 3 Mix design methods - Reference, MDLM, Mixsim
B	10	5 Cements – PC/SF (CEM II/A-D), PC/MK (CEM II/A-Q), PC/LS (CEM II/B-L), PC/PFA/SF (CEM V/A) and PC/PFA/MK (CEM V/A)
C	11	1 Cement – PC (CEM I) 5 Water contents 3 w/c ratios - 0.35, 0.45 and 0.55

The other cements, also to BS EN 197-1, used in Series B, were:

- Portland silica fume cement (PC/SF) comprising PC and 10% silica fume (SF).
- Portland pozzolana cement (PC/MK) comprising PC and 15% metakaolin (MK).
- Portland limestone cement (PC/LS) comprising PC and 15% crushed limestone (LS).
- Composite cement (PC/PFA/SF) comprising PC and 25% PFA and 5% SF.
- Composite cement (PC/PFA/MK) comprising PC and 25% PFA and 5% MK.

The chemical composition and physical properties of the PC and the five additions (PFA, GGBS, SF, MK and LS) are given in Table 3. The aggregate comprised natural gravel in 20-10mm and 10-5mm fractions and a medium grade (MP) sand conforming to BS EN 12620 [13]. Limestone filler to BS 12620 [13] (Table 3) was also used when required by the mix design method to minimise voids (Series A) and to maintain the fines content in cement reduced mixes (Series C). A superplasticizing admixture to BS EN 934: Part 2 [14] was also used to control workability in some cases.

4. MIX PROPORTIONS

The mix proportions were those used in several related studies [3, 5, 7], which were mainly aimed at optimising concrete performance, in particular for various aspects of durability. The basis of the mix proportioning was therefore different within and between series. Series A, carried out to assess the effect of physical packing for voids minimisation, used PC, PC/PFA and PC/GGBS and three mix design methods; (i) the BRE mix design method [15] as a reference, and two optimum packing methods, (ii) Mixsim'98 [1] and (iii) a Modified De Larrard method (MDLM) [3]. Mixsim'98 is a commercially available method, based on a packing model formulated by Dewar [1] in which the voids ratio is minimised, based on the assumption that in concrete and mortar there exists a coarse component within a fine component matrix. MDLM is a method, developed at the University of Dundee [3], based on De Larrard's linear packing model [2, 16], in which concrete is assumed to be a granular mixture, divided into n-number of quasi-monosized components of equal density, similarly shaped and non-deformable particle groups. Since the model can be used to calculate multi-particle systems with any n components, it makes it possible to determine the particle packing density of concrete for the full particle grading from the largest aggregate to the finest filler.

The mix proportions for **Series A** are given in Table 4(a). PC mixes were proportioned to enable comparison of the three mix design methods at four PC contents (250 kg/m³ to 400 kg/m³). Similarly, PC/PFA mixes were proportioned to enable comparison of the three mix design methods at five PC + PFA contents ranging from 195 kg/m³ to 380 kg/m³. In all cases, the mixes contained superplasticizing admixture, at dosages to give 75 mm slump. In comparison to the reference mixes, the particle packing methods generally enabled lower water (up to 20 l/m³ at the same admixture dosage) and sand (up to 320 kg/m³) contents to be used; with the yield maintained by use of LS filler and higher coarse aggregate contents. For the PC/GGBS mixes, the reference mixes had PC + GGBS contents of 270 kg/m³ and 390 kg/m³, compared with 300 kg/m³ and 400 kg/m³ used for the two packing mix proportions.

Series B consisted of concrete mixes of w/c ratio 0.64 and 0.46, using a variety of cement types, as given in Table 4(b). The mixes were based on the PC reference mixes A1R and A3R from Series A (Table 4a), and the water, PC + addition, and coarse aggregate contents were equal for all mixes at a given w/c ratio. The sand contents were adjusted to maintain yield.

Series C comprised mixes proportioned at three w/c ratios (0.55, 0.45, 0.35) using a range of cement (245-505 kg/m³) and water contents (195 – 135 l/m³). The mix proportions are given in Table 4(c). For reducing water contents below the 175 l/m³ level, ground LS filler (taken as part of the sand content in proportioning) was used to maintain the mix fines content at the C1, C6 and C9 mix levels. In addition, the aggregate contents were adjusted to maintain yield and superplasticizing admixture used, as required, to give workability of 75 mm slump.

Table 3 - Properties of cements and additions used in concrete mixes

PROPERTY	PC	PFA ^a	GGBS	SF	MK	LS
Fineness, m ² /kg	405	7.2 ^b	509	15750	3474	1600
Loss-on-Ignition, %	1.4	5.0	0.9	-	1.0	43.6
Particle Density	3.14	2.27	2.90	2.20	2.59	2.62
Main Bulk Oxide Compositions (% by mass)						
CaO	64.6	3.4	41.0	0.3	0.03	55.5
SiO ₂	21.0	46.9	35.8	95.3	55.1	-
Al ₂ O ₃	4.9	23.2	13.7	0.7	41.1	0.1
Fe ₂ O ₃	2.6	8.8	0.5	0.3	0.6	-
MgO	1.2	0.8	5.9	0.4	0.2	0.2
TiO ₂	-	1.5	0.4	-	-	-
K ₂ O	0.1	3.7	0.3	0.8	2.0	-
Na ₂ O	0.1	4.4	0.2	0.3	-	-
SO ₃	3.3	2.3	1.0	0.3	-	-
Bogue Compound Composition (% by mass)						
C ₃ S	53.0	-	-	-	-	-
C ₂ S	21.0	-	-	-	-	-
C ₃ A	8.5	-	-	-	-	-
C ₄ AF	8.0	-	-	-	-	-

^a Water Demand = 96%, Strength Factor = 0.88 ^b % retention on 45µm sieve

5. CUBE STRENGTHS

The 28 day cube strengths of all concrete mixes, measured in accordance with BS 1881: Part 116 [17], are given in Tables 4(a-c). Results from Series A indicate that for a given w/c ratio minor improvements were achieved using the optimum packing proportioning method. For example, the reference proportioning method for a w/c ratio of 0.40 (PC content, 400 kg/m³), gave a 28 day cube strength of 59.0 N/mm², whilst the corresponding Mixsim'98 proportioned concrete (PC content, 350 kg/m³) had a strength of 61.5 N/mm²; an increase of 4%. Similar behaviour was noted for the mixes containing PFA and GGBS. Given the reduced water demand of these mixes, the results suggest that this approach to mix proportioning may enable more efficient use of cement in concrete.

Compared with the PC mixes, concrete containing the various other cements (Series B) gave similar results to those noted elsewhere [18-21] when compared at equal w/c ratio. For example, at 28 days, PC/PFA and PC/GGBS concretes gave cube strengths of 7-12 N/mm² and 6-10 N/mm² lower, respectively than PC concrete. On the other hand, PC/SF mixes gave the highest cube strengths, which were approximately 15% higher than PC concrete, whilst both PC/MK and PC/PFA/SF mixes gave similar strengths (to the PC mixes). All of the other cement types gave strengths lower than PC at the same w/c ratio.

Similar benefits to those of particle packing were found through changing the cement and water contents at a given w/c ratio, with the inclusion of filler and superplasticizer to

maintain the fines content and workability (Series C). For example, at a w/c ratio of 0.55, a reduction in water content of 40 l/m³ from 175 l/m³ to 135 l/m³ (and a reduction in cement content of up to 70 kg/m³) gave an increase in cube strength of up to 10.0 N/mm².

6. ENGINEERING PROPERTIES

Tensile splitting strength, flexural strength and static elastic modulus were tested in accordance with BS 1881: Parts 117, 118 and 121 [22-24], respectively.

6.1 Flexural and Tensile Splitting Strength

The relationships between cube strength (f_{cc}) and flexural strength ($f_{ct,fl}$), and cube strength and tensile splitting strength ($f_{ct,sp}$) for Series A and Series B mixes are given in Figure 1, and compared with the respective design approximations given in Table 1, which are based on EC2 [8] and RILEM TC 162 [25], with $f_{ct,sp}$ assumed equal to $0.6 f_{ct,fl}$ [26]. All of the results fell within $\pm 5\%$ of the standard relationships (shown by the dotted lines) and were independent of the mix design method or cement type, and appear to justify the assumption that flexural and tensile strength are proportional to $f_{cc}^{2/3}$. However, there appears to be slightly more scatter for the flexural strength results than those of tensile strength. This is partly because of the tendency for physically packed concrete mixes containing PFA to have a slightly higher flexural strength at a given cube strength than the other mixes. This may be due to the lower voids ratio of these concrete mixes as shown by the relationship between $f_{ct,fl}/f_{cc}^{2/3}$ and the voids ratio,

Table 4(a) - Mix proportions for Series A

MIX	W/C	MIX CONSTITUENTS, kg/m ³								f _{cc} , N/mm ²
		CEMENTS/ADDITIONS			LS FILLER	FREE WATER	AGGREGATES			
		PC	PFA	GGBS			sand	5-10mm	10-20mm	
PC - Reference										
A1R [§]	0.64	250	-	-	-	160	835	390	785	34.5
A2R	0.53	300	-	-	-	160	755	400	805	46.5
A3R [§]	0.46	350	-	-	-	160	705	400	800	49.0
A4R	0.40	400	-	-	-	160	670	395	795	59.0
PC - MDLM										
A1D [§]	0.56	250	-	-	45	140	590	350	1030	44.0
A2D	0.47	300	-	-	-	140	580	410	975	53.5
A3D [§]	0.40	350	-	-	-	140	475	395	1095	59.5
A4D	0.35	400	-	-	-	140	350	435	1095	67.0
PC – Mixsim										
A1M [§]	0.56	250	-	-	55	140	655	435	870	48.0
A2M	0.47	300	-	-	25	140	630	440	880	52.0
A3M [§]	0.40	350	-	-	25	140	545	455	905	61.5
A4M	0.35	400	-	-	35	140	440	475	950	65.5
PC/PFA – Reference										
A5R	0.82	135	60	-	-	160	865	375	750	13.0
A6R [§]	0.64	175	75	-	-	160	785	385	770	22.5
A7R	0.56	200	85	-	-	160	750	385	770	29.5
A8R	0.50	225	95	-	-	160	715	385	770	34.0
A9R [§]	0.42	265	115	-	-	160	665	385	770	50.0
PC/PFA – MDLM										
A5D	0.75	135	60	-	30	145	630	320	1045	17.0
A6D [§]	0.58	175	75	-	30	145	590	355	1000	27.0
A7D	0.56	200	85	-	15	145	570	395	960	35.5
A8D	0.46	225	95	-	-	145	515	435	955	40.0
A9D [§]	0.38	265	115	-	-	145	405	485	960	48.0
PC/PFA – Mixsim										
A5M	0.75	135	60	-	30	145	755	415	830	16.0
A6M [§]	0.58	175	75	-	40	145	690	415	835	25.5
A7M	0.56	200	85	-	40	145	645	420	845	34.0
A8M	0.45	225	95	-	35	145	600	425	850	38.0
A9M [§]	0.38	265	115	-	35	145	490	440	885	47.5
PC/GGBS – Reference										
A10R [§]	0.59	160	-	110	-	160	775	390	775	32.0
A11R [§]	0.41	235	-	155	-	160	740	375	745	50.0
PC/GGBS – MDLM										
A10D [§]	0.45	180	-	120	20	145	585	395	950	44.0
A11D [§]	0.38	240	-	160	-	150	415	470	975	48.0
PC/GGBS - Mixsim										
A10M [§]	0.45	180	-	120	35	150	630	430	855	48.0
A11M [§]	0.34	240	-	160	35	145	450	460	915	59.5

calculated using Dewar's method [1], in Figure 2. As the voids ratio fell below 0.2 (i.e. for concretes containing PFA), there was a noticeable increase in ratio between $f_{ct,fl}$ and $f_{cc}^{2/3}$ from a value of 0.35 to 0.40.

That the results fall within $\pm 5\%$ of the standard relationships is interesting, since the effects of particle packing and associated reductions in cement content (for a given w/c) on flexural and tensile strength may have been expected to vary slightly from the effects on cube strength,

due to the different failure mechanisms occurring. In particular, reduced cement content may reduce contact at the bond interface between the coarse aggregate and cementing component, and may have been expected to be greater in MDLM mixes, which contain the highest quantities of aggregate in proportion to cement. Clearly, these effects do not have a significant impact on engineering property relationships.

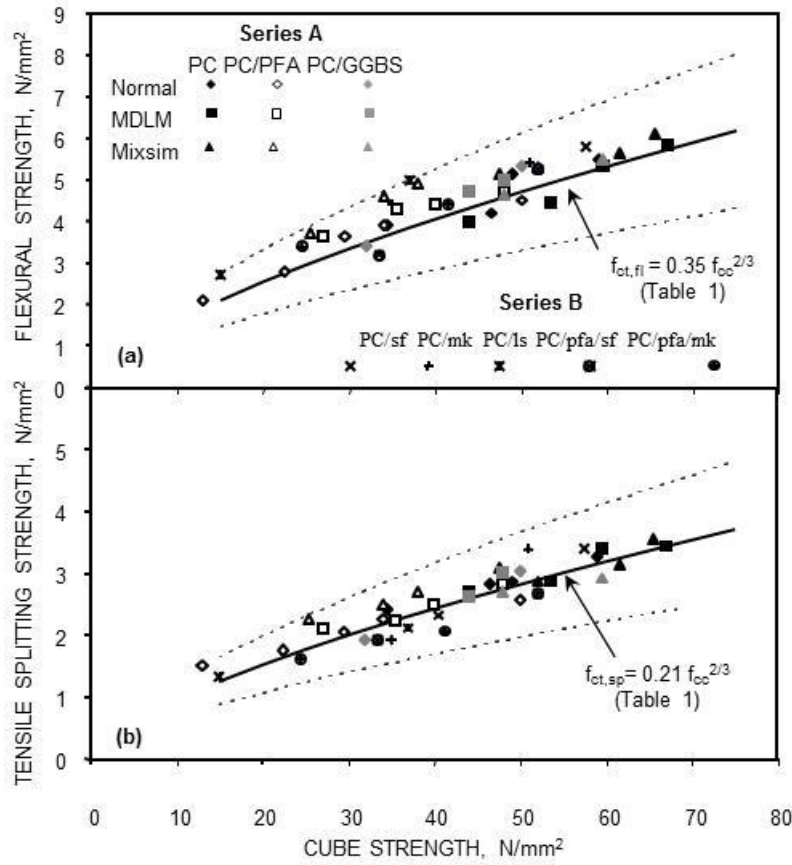


Fig. 1 - Effect of cement type and physical packing on relationship between cube strength and (a) flexural strength and (b) tensile splitting strength

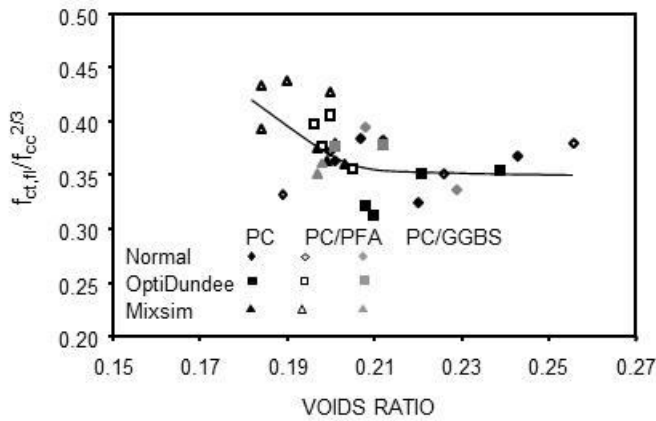


Fig. 2 - Effect of voids ratio on $f_{ct,fl}/f_{cc}^{2/3}$ ratio

Table 4(b) - Mix proportions for Series B

MIX	W/C	MIX CONSTITUENTS, kg/m ³									f _{cc} , N/mm ²
		CEMENTS/ADDITIONS					FREE WATER	AGGREGATES			
		PC	PFA	SF	MK	LS		sand	5-10mm	10-20mm	
A1R [§]	0.64	250	-	-	-	-	160	835	390	785	34.5
A3R [§]	0.46	350	-	-	-	-	160	705	400	800	49.0
B1 [§]	0.64	225	-	25	-	-	160	800	390	785	40.5
B2 [§]	0.46	315	-	35	-	-	160	695	400	800	57.5
B3 [§]	0.64	210	-	-	40	-	160	810	390	785	35.0
B4 [§]	0.46	300	-	-	50	-	160	700	400	800	51.0
B5 [§]	0.64	190	-	-	-	60	160	810	390	785	15.0
B6 [§]	0.46	260	-	-	-	90	160	695	400	800	37.0
B7 [§]	0.64	175	65	15	-	-	160	795	390	785	24.5
B8 [§]	0.46	245	90	20	-	-	160	675	400	800	41.5
B9 [§]	0.64	175	65	-	15	-	160	795	390	785	33.5
B10 [§]	0.46	245	90	-	20	-	160	675	400	800	52.0

[§] mixes selectively used for reinforced concrete beam tests

Table 4(c) - Mix proportions for Series C

MIX	MIX CONSTITUENTS, kg/m ³						f _{cc} , N/mm ²
	PC	LS FILLER	FREE WATER	AGGREGATES			
				sand	5-10mm	10-20mm	
<i>w/c = 0.55</i>							
C5*§	355	0	195	630	390	780	38.5
C4*§	320	0	175	660	410	815	41.0
C1§	320	0	175	565	440	880	41.5
C2§	280	40	155	550	460	920	44.0
C3§	245	75	135	540	480	955	48.0
<i>w/c = 0.45</i>							
C6§	390	0	175	510	435	875	53.5
C7§	345	45	155	490	455	920	55.5
C8	300	90	135	470	480	960	59.5
<i>w/c = 0.35</i>							
C9§	505	0	175	395	445	885	69.5
C10§	450	55	155	365	470	935	71.0
C11	390	115	135	325	495	985	74.0

All mixes nominal slump of 75 mm, except * 180 mm slump

[§] mixes selectively used for reinforced concrete beam tests

Tests for flexural strength (Figure 3) for Series C mixes showed similar relationships to those of Series A and Series B (Figure 1a), with the data points

again falling within $\pm 5\%$ of the standard relationships. Similar behaviour was noted for tensile splitting strength. However, it can be seen that for any given cube strength,

the mixes with higher cement contents tended to have higher flexural strengths. This is clearly shown in the relationship between cement content and $f_{ct,fl}/f_{cc}^{2/3}$ in Figure 4. For a given w/c ratio, lower cement contents gave a lower ratio of $f_{ct,fl}/f_{cc}^{2/3}$. This suggests that higher cube strength, achieved through cement reduction at a given w/c ratio (Table 4(c)), did not give an increase in flexural strength, indicating slightly greater brittleness in these cases. However, all values of $f_{ct,fl}/f_{cc}^{2/3}$ were higher than that given in EC2 [8].

6.2 Elastic Modulus

The relationships between elastic modulus and cube strength for Series A and Series B are shown in Figure 5(a). The degree of scatter was low, suggesting that the effect of physical packing and cement type on elastic modulus was similar to the effect on cube strength. This was, to some extent, expected, since the intention of particle packing is to fill the voids within concrete, thus providing greater resistance to load and deformation. However, since particle packing enabled a lower cement content to be used for a given strength, this reduced the level of relatively low elastic modulus cement paste in the concrete, and increased the high elastic modulus coarse and fine aggregate. Clearly, for the changes to mix proportions used in this study, there was no significant influence on elastic modulus.

Similarly in Series C, where a given cube strength was achieved with lower cement contents, the lower volume of cement paste may have been expected to lead to higher elastic modulus. However, again the results suggest that there was no effect of cement content on the elastic modulus – cube strength relationship, with all results, Figure 5(b), falling within a narrow band and exhibiting low scatter. Thus, it would appear (over the range tested) that the effects of particle packing, cement type and cement content on elastic modulus can be related directly to cube strength and is independent of mix proportions, as currently followed in EC2 design procedures [8].

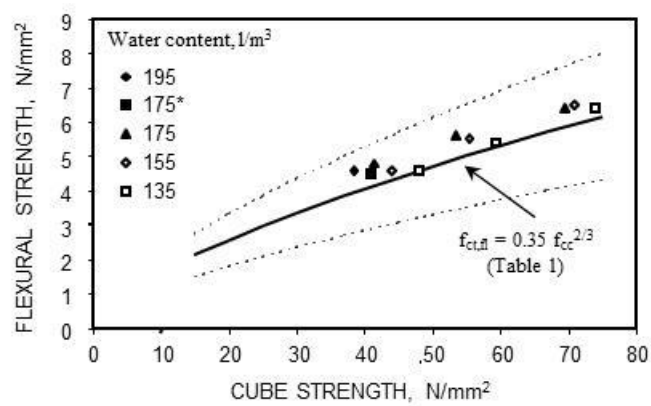


Fig. 3 – Effect of water content on relationship between cube strength and tensile strength

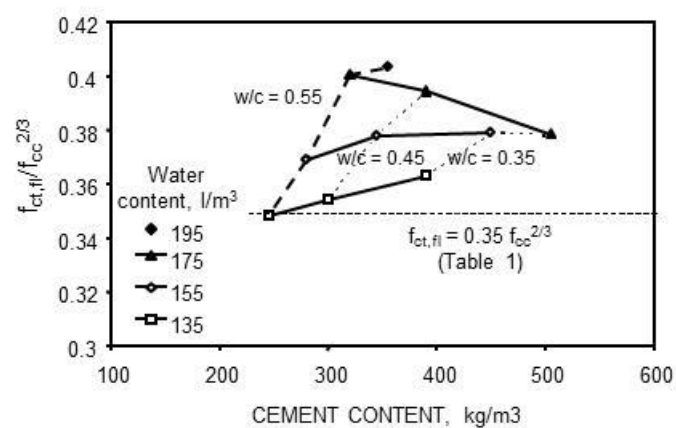


Fig. 4 - Effect of cement content on on $f_{ct,fl}/f_{cc}^{2/3}$ ratio

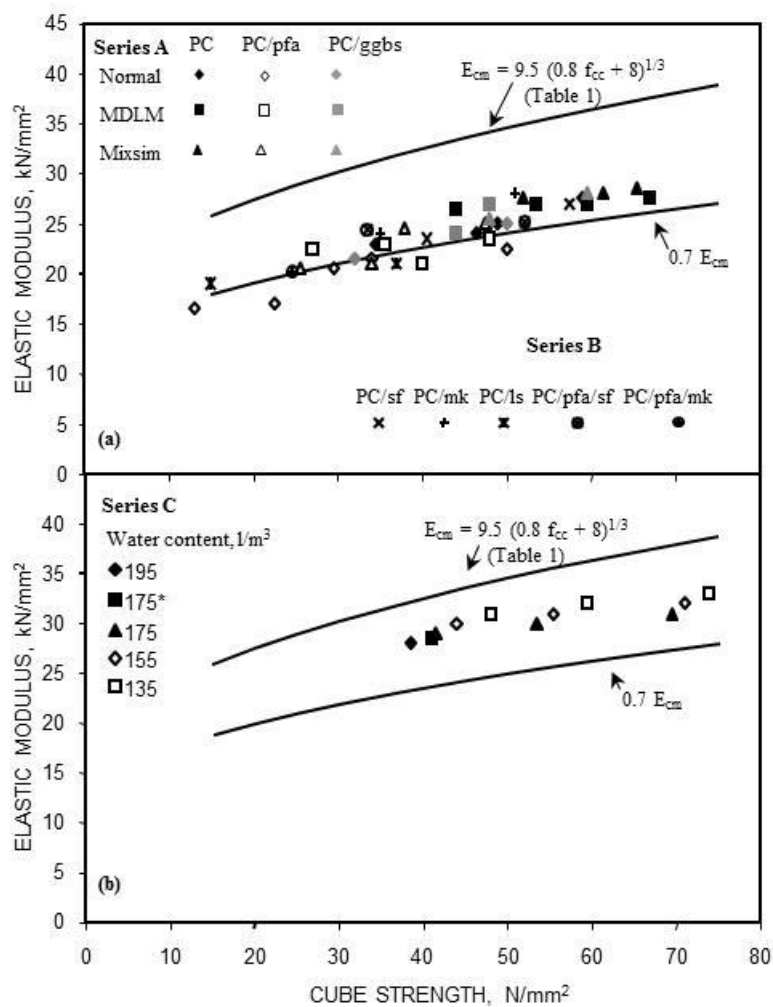


Fig. 5 - Effect of (a) cement type and particle packing and (b) cement and water content on relationship between cube strength and elastic modulus

Table 5 - Cube strength and Shear Strength for physical packing optimised mixes used in reinforced concrete beam tests

	f_{cc} N/mm ²	V kN	$\mu\epsilon$	$V_{Rd,ct}$ kN	V/ $V_{Rd,ctk}$
(a) Series A					
<i>PC</i>					
A1R	26.5	55	152	60	0.92
A3R	37.0	81	147	67	1.21
A1D	34.0	71	173	65	1.09
A3D	44.0	83	198	71	1.17
A1M	31.0	72	202	63	1.14
A3M	43.5	81	203	70	1.15
<i>PC/PFA</i>					
A6R	15.5	54	136	50	1.08
A9R	31.0	72	179	63	1.14
A6D	24.5	62	250	58	1.06
A9D	33.0	76	272	64	1.18
A6M	23.5	57	242	57	0.99
A9M	33.0	75	207	64	1.16
<i>PC/GGBS</i>					
A10R	26.0	65	182	59	1.09
A11R	38.0	77	249	67	1.14
A10D	39.5	74	173	68	1.08
A11D	45.5	80	172	71	1.12
A10M	38.0	72	168	67	1.07
A11M	44.5	77	119	71	1.08
(b) Series B					
B1	40.5	65	180	69	0.94
B2	57.5	79	256	77	1.02
B3	35.0	68	160	66	1.04
B4	51.0	77	210	74	1.04
B5	15.0	55	151	49	1.11
B6	37.0	75	173	67	1.12
B7	24.5	53	148	58	0.91
B8	41.5	66	240	69	0.95
B9	33.5	61	228	65	0.94
B10	52.0	75	190	75	1.00
(c) Series C					
<i>W/C = 0.55</i>					
C5*	26.5	63	190	60	1.06
C4*	28.5	67	200	61	1.03
C1	28.0	66	170	61	1.04
C2	28.5	68	164	61	1.11
C3	29.5	71	155	62	1.15
<i>W/C = 0.45</i>					
C6	36.0	70	167	66	1.06
C7	38.0	70	199	67	1.04
<i>W/C = 0.35</i>					
C9	47.0	80	183	72	1.11
C10	51.5	74	196	74	1.00

$\mu\epsilon$ = microstrain at ultimate load

It should be noted that for all series, the elastic moduli fell below the mean line predicted by EC2. This reflects the characteristics of the natural gravel aggregates used in the study, which are known to give concretes of relatively low elastic modulus [27]. For this reason, the FIP document on practical design of structural concrete [28] recognises that elastic modulus may fall between $0.7 E_{cm}$ and $1.3 E_{cm}$ of the mean figure, depending on aggregate and cement type. The results of this study suggest that for the aggregates used in this study, $0.7 E_{cm}$ fits the data best and that cement type had no influence.

7. STRUCTURAL PERFORMANCE

The structural performance of reinforced concrete is influenced by a combination of the concrete engineering properties, steel reinforcement properties and concrete-steel interfacial properties. The performance and effect of the concrete engineering and concrete-steel interfacial properties are normally approximated in structural design, through the use of compressive strength, on the assumption that the effects of mix proportions on compressive strength have equivalent influences on these other properties. In general, this study has shown that the above assumption applies on an individual engineering property relationship basis. The next stage was concerned with the use of the concrete mixes described above in full-scale structural elements, to investigate the effect of the combined interaction of engineering properties and concrete-steel interfacial properties.

Tests on reinforced concrete beams cast using a selection of 37 previously investigated concrete mixes, identified by § in Tables 4a- 4c, were carried out. The properties of the beam and set-up for the tests are given in Figure 6. The reinforced concrete beams were tested to failure in three-point (centre point) loading, over an effective span of 1.9m. The tests were load-controlled, with the load added in increments of approximately 10 kN. A data logger was used to automatically record load, deflection and strain data. Two nominally identical tests were carried out on each of the mix combinations tested, i.e. a total of 74 reinforced concrete beams were tested in this study.

All test beams failed in a brittle manner by means of diagonal-tension, with little or no warning prior to ultimate failure, as expected for beams of reinforcement ratio ($A_s/b_w d$) of 1.8% tested over a shear span to effective depth ratio of 3.6. Typical shear force/deflection relationships are shown in Figure 7. No substantial post-cracking load was measured for any of the beams. Typical shear force-strain relationships (mid-span) are shown in Figure 8 and indicate that there was a linear relationship between strain (ϵ) and shear load up to approximately 75-80% of the ultimate load, suggesting that significant micro-cracking took place at this load. However, these cracks did not appear to significantly affect the stiffness of the beams, as demonstrated by the shear force/deflection relationships. Similar behaviour was noted for all beams, independent of the mix constituents or proportioning method used. The maximum shear force (V) and the strain at this force, for all beams, are given in Table 5.

The relationship between measured shear strength (v) and $[(1+(200/d)^{1/2}) (100 \rho f_{cc})^{1/3}]$ (see Eqn 1) is shown in Figure 9, and demonstrates that all test results were well above the design values, i.e. $v > v_{Rd,ct}$. Indeed, the measured shear strengths are shown to closely approximate to the characteristic shear capacity (where the partial safety factor of 1.5 has been removed from Eqn 1) given by:

$$\begin{aligned} v_{Rd,ctk} &= V_{Rd,ctk}/b_w d \\ &= [0.167 (1+(200/d)^{1/2}) (100 \rho f_{cc})^{1/3}] \end{aligned} \quad (2)$$

Table 5(a-c) compares the experimentally observed shear capacities (V) with the characteristic shear capacity ($V_{Rd,ctk}$). The results show that the mean value of the ratio $V/V_{Rd,ctk}$ was approximately 1.07 to 1.11. Therefore, the results suggest that the EC2 rule for predicting shear strength, based on compressive strength, is safe for concretes proportioned both through traditional methods and via modern techniques, i.e. by physical packing of mixes, through use of a wider range of cements or by reducing the cement content at a given w/c ratio and utilising ground LS filler and superplasticizing admixtures.

8. PRACTICAL IMPLICATIONS

Recent moves towards producing sustainable and/or durable concrete have seen the introduction of the use of alternative cements and more efficient mix design methods. Whilst it is widely accepted that these materials and methods can bring specific benefits to concrete, there has been concern that because of changes in the material composition and structure, these types of concrete may not be compatible with commonly accepted structural design rules.

The work reported has shown that the new concrete technology solutions may result in differences in compressive strength at a given w/c ratio. However, these differences are in the main proportionally carried over to other aspects of engineering performance (i.e. flexural strength, tensile splitting strength and elastic modulus).

Furthermore, it has been shown that there is no need for any review of general design procedures related to flexure or shear, on account of differences in behaviour between “normal” concrete mixes and the newer mix packages, with regard to relationships between compressive strength and other engineering properties. For this reason, they can be utilised effectively within the framework of present design procedures. Furthermore, engineers and specifiers can have much more control and flexibility in their approach to the concrete they use, in the knowledge that compressive strength is appropriate for assessing the structural performance of a concrete mix.

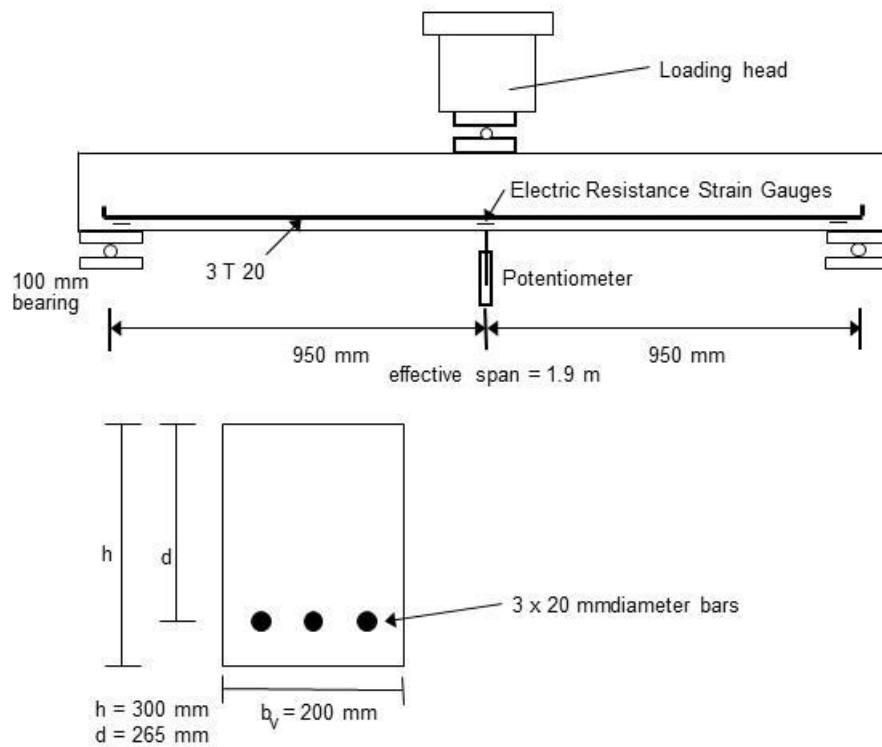


Fig. 6 - Test arrangement for reinforced concrete beam tests

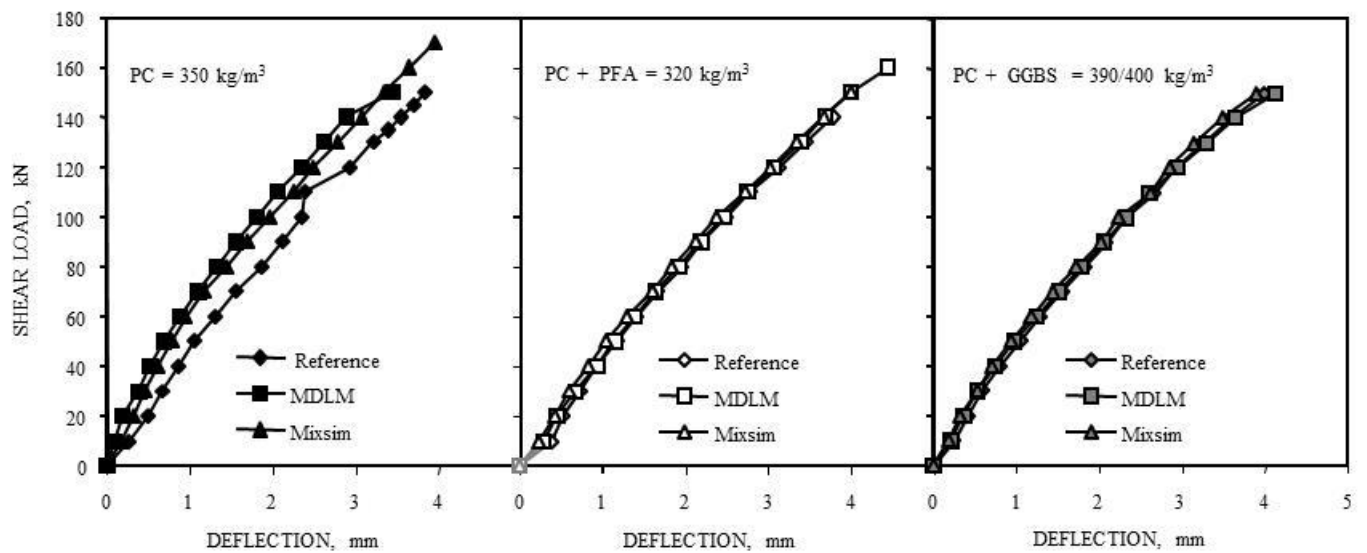


Fig. 7 - Shear load v deflection relationships for Series A beams

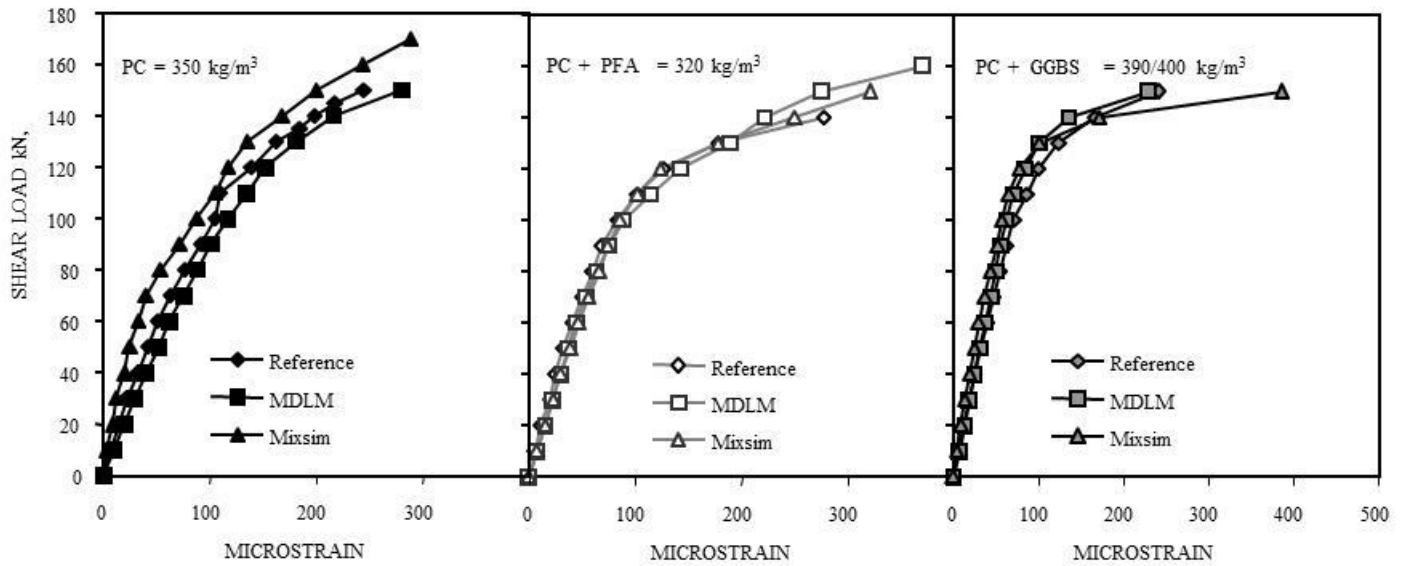


Fig. 8 - Shear load v steel strain relationships for Series A beams

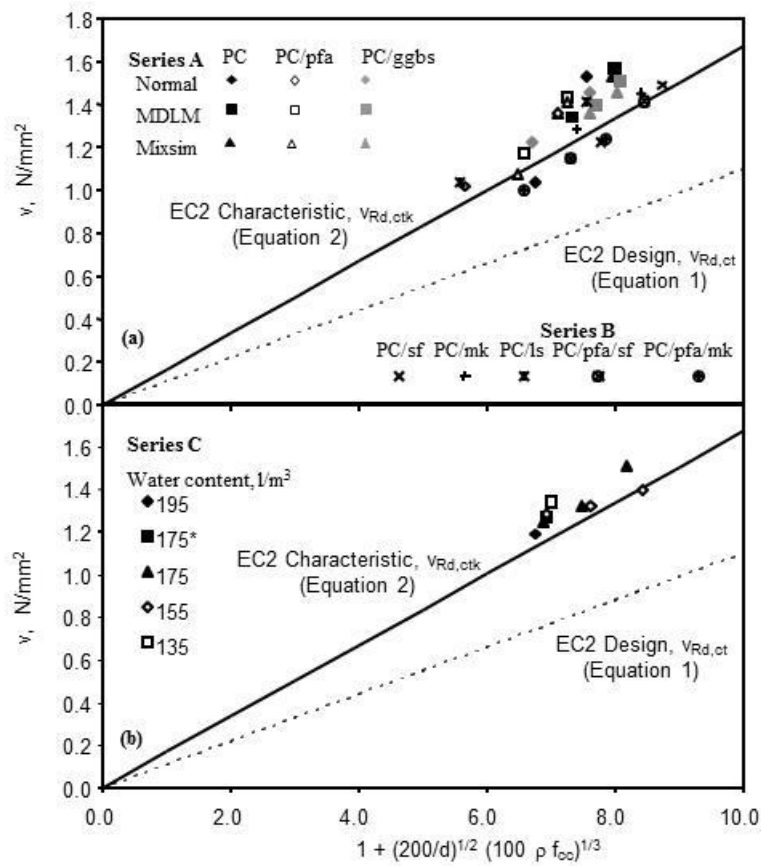


Fig. 9 - Relationship between measured shear strength (v) and EC2 design equations for (a) Series A and B, and (b) Series C beams

9. CONCLUSIONS

The research has shown that new and developing concrete technology solutions that improve concrete durability and/or achieve sustainable concrete construction, can be used effectively within the framework of present design procedures. In particular it was observed that:

1. A reduction in water content, facilitated by void minimisation techniques (particle packing) or through use of superplasticizers, at a given w/c ratio with the fines content maintained through the use of filler (i.e. lower cement content) results in concrete with a higher cube strength.
2. Changes in the performance of other engineering properties when using particle packing techniques, different cement types and lower water and cement contents are proportional to the changes in cube strength. Accepted and assumed relationships between engineering properties and compressive strength as used in most design codes are therefore valid.
3. The use of compressive strength in the EC2 equation for predicting the shear strength of reinforced concrete beams is valid for all types of concrete and constituents. No changes in the performance of these members in shear were observed.

Fig. 9 – Relationship between measured shear strength (v) and EC2 design equations for (a) Series A and B, and (b) Series C beams.

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